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A Scaled Hybrid Integrated Multiplier from 10 to 30 GHz

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Frequency multipliers which are built on a dielectric substrate have many useful applications in radio systems. The multiplier circuits which include input and output filters, idler circuits, and matching networks can be produced by integrated circuit processing techniques. Varactor diodes, also made by batch processing, can be bonded to the metallized substrate.

A hybrid integrated three-times frequency multiplier from 10 to 30 GHz has been designed and built on a silica substrate by using frequency scaling and integrated circuit processing techniques. The multiplier produces a CW output power of 50 mW for a pump power of 178 mW with an overall efficiency of 29 percent. The maximum output power is 150 mW. Other harmonic generators with different output frequencies can be built by scaling the existing circuit.

I. INTRODUCTION

Frequency multipliers are used in radio systems for downconverters, for upconverters, or for locking solid state oscillators. A typical example is the multiplier chain used in the short hop radio system experiment[1] which delivers 100 mW at 10.46 GHz for the transmitter and 10 mW at 10.66 GHz for the receiver. Similar systems above 10 GHz for common carrier applications will require a few tens of milliwatts of transmitter power[2] and approximately 10 mW for the receiving downconverter. A compact and low-cost repeater package can be manufactured by using integrated circuit technology for building components and subassemblies. This can be achieved by using low-loss dielectric substrates, fully shielded circuits, and a circuit design which does not require high Q factors.

All three basic requirements are fulfilled for the frequency multi-

plier described in this paper. The dielectric substrate is silica, the circuit is fully shielded, and low-Q filters are used for separating the pump frequency and the output frequency. The pump frequency is compatible with the output of existing high-efficiency multipliers used in the short hop system experiment.[1] The substrate metallization as well as the planar diffused GaAs varactor diodes are fabricated by using integrated circuit processing steps. Optimum dimensions of all conductor patterns are obtained by building and testing an oversize model of the complete multiplier at a lower frequency, that is, with a pump frequency of 270 MHz and an output frequency of 810 MHz. Circuit adjustments are easily made in the oversize multiplier and no adjustments are necessary after the oversize model is reduced to its final size. Good stability and spurious-free operation is obtained for the oversize multiplier with an 80 percent efficiency and a power output of 2.5 W at 818 MHz.

II. DESIGN AND FABRICATION OF INTEGRATED MULTIPLIERS

Frequency multipliers have been built in the past with coaxial and waveguide circuits by using mesa type,[3] or planar diffused, Si or GaAs[4] varactor diodes with the highest possible figure of merit.[5] The basic design principles for building multipliers are well known[5–7] and overall efficiencies close to the theoretically expected values have been achieved up to X-band frequencies. Some effort has been made in building high-performance hybrid integrated multipliers up to X-band, but the design of good filters on commonly used alumina substrates is difficult at millimeter-wave frequencies and also external tuning elements are usually needed to achieve good overall efficiency. This difficulty can be resolved by using a high-quality dielectric substrate with a relatively low dielectric constant and a simple conductor pattern which can be clearly separated into a low-pass input filter, an idler circuit, and a band-pass filter. Before scaling, the filter characteristics and the performance of the complete multiplier are tested in an oversize model. The model is assembled with clear silica plates with a relative dielectric constant $\varepsilon_r = 3.8$. Small air gaps in the oversize model between the ground plane and the dielectric substrate and air gaps between the conductor pattern and the substrate are not critical because of the low dielectric constant of silica. The junction capacitance and the dimensions of the varactor diode are also scaled by the same reduction factor which is used for scaling the microstrip circuit. The parameters which are more difficult to scale are the cutoff fre-

quency of the diode and the skin depth of the microstrip conductors. This problem has been reduced by using a low-cutoff silicon diode for the low-frequency model and a high-cutoff gallium arsenide diode in the final circuit at 30 GHz. The skin depth is partially scaled by using brass conductors for the low-frequency model and gold conductors for the final circuit.

2.1 *Multiplier Conductor Pattern*

Tho complete conductor pattern of the multiplier deposited on a silica substrate is shown in Fig. 1. The pattern consists of three sections, a low-pass input filter, an idler section, and a band-pass output filter. The input and the output is a microstrip line with a characteristic impedance of 50 ohms. The substrate is inserted into a channel in a brass block, shown in Fig. 2, with a coaxial-to-microstrip transition at the input and a microstrip-to-waveguide transition at the output. A planar diffused GaAs varactor diode is mounted between the substrate metallization and a metal tab which is in contact with one sidewall of the channel shown in Fig. 2. The multiplier is completely shielded by a metal plate which covers the brass channel.

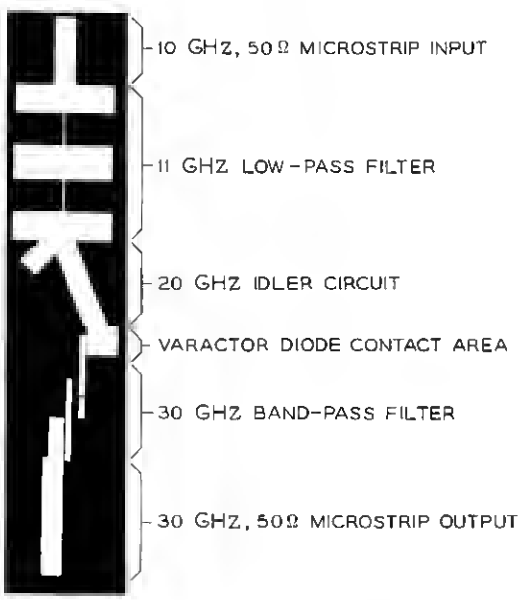

Fig. 1—Conductor pattern of hybrid integrated multiplier on silica substrate.

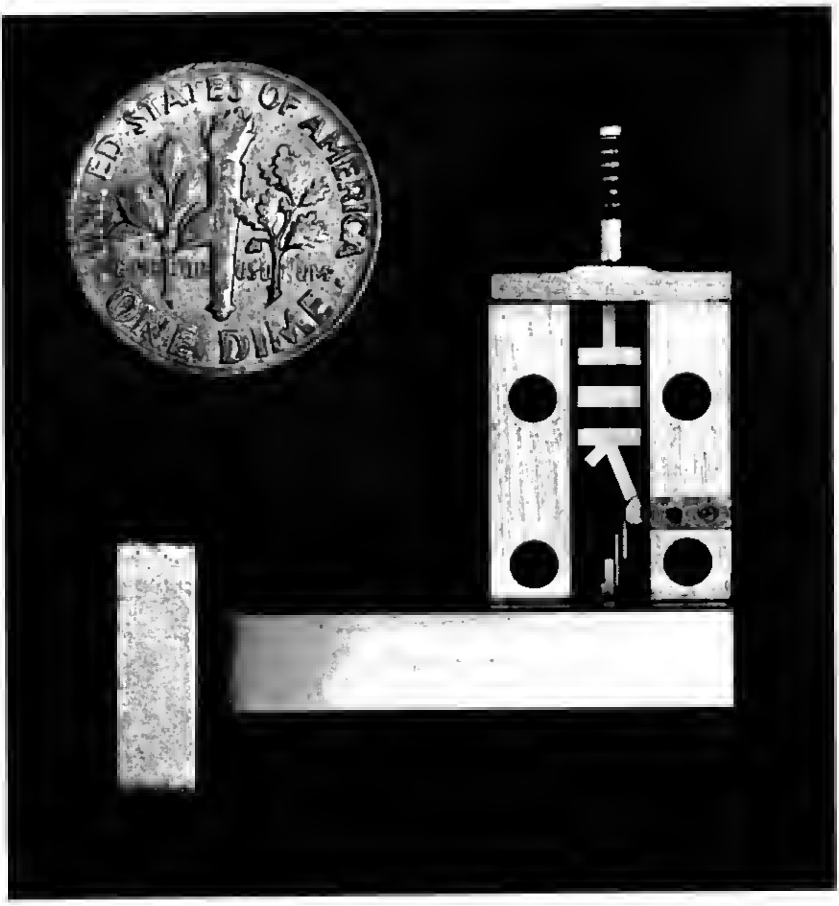

Fig. 2—Hybrid integrated multiplier from 10 GHz to 30 GHz with transitions from coaxial transmission line to microstrip, and microstrip to RG-96/U waveguide.

2.2 *Low-Pass and Band-Pass Filter Design*

The low-pass filter used in the multiplier is a five element semi-lumped structure consisting of three capacitive and two inductive sections. The element values for a Chebyshev filter with a 0.2-dB ripple are computed from tables given by G. L. Matthaei.[8] The cutoff frequency is 300 MHz for the oversize model and 11.2 GHz for the scaled filter. The attenuation of the filter at the second harmonic of the pump frequency, which is the idler frequency of the multiplier, is 35 dB.

The band-pass filter consists of two parallel-coupled microstrip resonators. The 3-dB bandwidth of the oversize filter with a center frequency of 810 MHz is 160 MHz. The 3-dB bandwidth of the reduced filter with a center frequency of 30.4 GHz is 6.0 GHz. The attenuation of the filter at the second harmonic of the pump frequency is 25 dB. The scaling of microstrip circuits, the design of the filters, and the measured characteristics of low-pass and band-pass microstrip filters on silica are described in more detail in a separate paper.[9]

The input and output impedance for each filter is 50 ohms. An additional matching network or a modification of each filter is necessary to match the input impedance Z_{in} and the output impedance Z_{out} of the multiplier. Z_{in} and Z_{out} are functions of the pump frequency ω_o, the nonlinearity coefficient γ, the breakdown capacitance C_B, and the drive D of the varactor diode. For a tripler with $f_o = \omega_o/2\pi = 10$ GHz, a nonlinearity coefficient $\gamma = 0.33$, a breakdown capacitance $C_B = 0.090$ pF, and a drive $D = 1.6$, one obtains

$$Z_{in} = \frac{F_1(\gamma, D)}{\omega_o C_B} = \frac{0.214}{\omega_o C_B} = 38\ \Omega, \tag{1}$$

$$Z_{out} = \frac{F_2(\gamma, D)}{\omega_o C_B} = \frac{0.087}{\omega_o C_B} = 15.5\ \Omega, \tag{2}$$

where the values of the functions $F_1(\gamma, D)$ and $F_2(\gamma, D)$ are obtained from tables given by C. B. Burckhardt.[6] The transformation from 38 ohms to 50 ohms at the input is achieved by a quarter-wave microstrip section with an impedance of $Z = \sqrt{50 Z_{in}} = 43.5\ \Omega$. This section is also part of the idler circuit shown in Fig. 1. Its electrical length at the idler frequency is slightly longer than half a wavelength and its inductive reactance seen across the varactor terminal resonates with the average diode capacitance at the idler frequency. A short additional line section is required to tune the reactive part of the diode package.

The transformation from 15.5 ohms to 50 ohms is obtained by adjusting the coupling between the contact area of the varactor diode and the adjacent half-wavelength microstrip resonator. The spacing between the conductor edges is optimized in the oversize model of the multiplier and no adjustment is necessary after the model is reduced to its final size.

2.3 *Diode Fabrication and Packaging*

The planar diode used for the integrated multiplier is a zinc-diffused junction in n-type epitaxial gallium arsenide with a doping level of

2×10^{17} carriers/cc and an epitaxial layer thickness of 1.2 μm. The processing is done by the photoresist, etching, and zinc-diffusion process developed by C. A. Burrus[10] for fabricating planar millimeter-wave varactor diodes with zero-bias cutoff frequencies above 500 GHz for breakdown voltages between 10 and 20 volts. Contact to the gold-plated junction with a diameter of 20 μm is made with a gold wire with a diameter of 75 μm and a length of 150 μm. The gold wire is embedded in epoxy and the diode is mounted in the circuit between the gold-plated contact area on the silica substrate and a spring-loaded ground contact made with a gold-plated phosphor bronze tab which is shown in Fig. 2. The diodes can be easily replaced and the mount has the smallest possible series inductance which can be achieved without making a hole in the silica substrate.

III. PERFORMANCE OF HYBRID INTEGRATED MULTIPLIER

The microstrip and diode properties used for building the hybrid integrated multiplier are listed in Table I. The output power of this multiplier is 50 mW at 30.3 GHz for a pump power of 178 mW at 10.1 GHz. The available output power at burnout is 150 mW. A plot of the output power as a function of pump power is shown in Fig. 3 and specific performance data are listed in Table II.

The output is measured in RG-96/U rectangular waveguide by using a microstrip-to-waveguide transition which is similar to the side launcher developed by K. H. Knerr.[11] The only major difference is that the Knerr launcher is used for balanced microstrip line while the pres-

TABLE I—SUBSTRATE AND DIODE PROPERTIES

Substrate Material	Silica
Dielectric Constant	$\epsilon_r = 3.828 \pm 0.003$ at 8.5 GHz
Loss Tangent	$10^4 \cdot \tan \delta = 1.29 \pm 0.2$ at 8.5 GHz
Substrate Thickness	0.34 mm
Substrate Dimensions	4.06 mm $\times$ 20.4 mm
Substrate Metallization	100 Å Nichrome and 1000 Å Gold evaporated, 3 μm Gold electroplated
Weight of Gold	4.7 milligrams (0.57 cent)
Varactor Diode	Planar zinc-diffused junction into epitaxial GaAs N/N^+
Epitaxial Layer Thickness	1.2 μm
Doping Level	1.9×10^{17} carriers/cc
Mobility and Resistivity	4290 cm²/Vsec, 0.0076 Ωcm
Properties of N^+ Material	Orientation ⟨100⟩, Te doped, 1×10^{-3} Ωcm
Junction Diameter	20 μm
Wafer Thickness	0.20 mm
Wafer Dimensions	0.35 $\times$ 0.35 mm

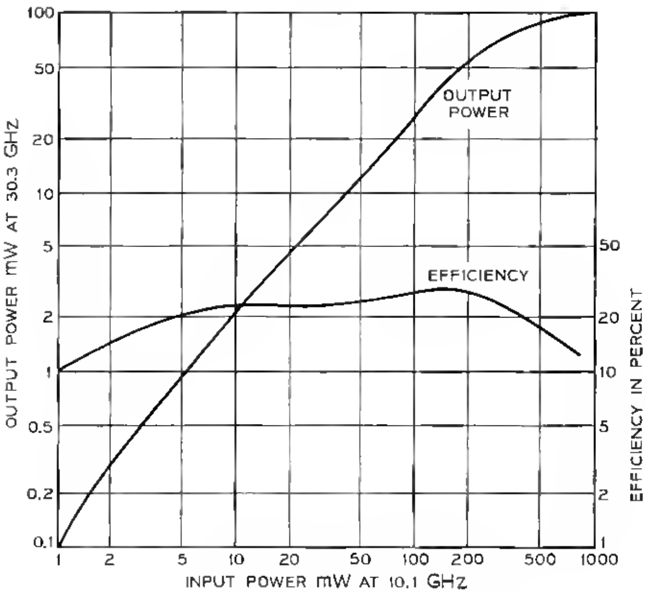

Fig. 3—Output power of multiplier at 30.3 GHz as a function of pump power at 10.1 GHz.

Table II—Integrated Frequency Multiplier Performance

Input Frequency	10.1 GHz
Input Power	178 mW
Output Frequency	30.3 GHz
Output Power	50 mW
Efficiency	29%
DC-Bias	Self-bias, 6 mA at 3V
Capacitance at Zero Bias	0.15 pF
Capacitance at Breakdown	0.09 pF
Breakdown Voltage	15 volts
Input Microstrip Filter	Five element semi-lumped low-pass filter with three capacitive and two inductive sections, cutoff frequency 11.2 GHz
Output Microstrip Filter	Band-pass filter with two parallel-coupled microstrip resonators, center frequency 30.4 GHz, 3-dB bandwidth 6 GHz
Input of Multiplier	Coaxial-to-microstrip transition, 50-ohm coax to 50-ohm microstrip
Output of Multiplier	Microstrip-to-waveguide transition, 50-ohm microstrip to RG-96/U waveguide

ent launcher is optimized for a standard microstrip line on a silica substrate.

The tuned output power versus frequency for a pump power of 137 mW is plotted in Fig. 4. The 3-dB bandwidth is 2.5 GHz or 8.5 percent and has been achieved by optimizing both diode bias voltage and plunger position of the microstrip-to-waveguide transisition at each frequency. The maximum output power is obtained at 30.3 GHz and is related to the fixed frequency resonance of the idler which occurs at 20.2 GHz. The corresponding oversize multiplier is optimized for an input frequency of 272.7 MHz and an output at 818 MHz. The scaling factor used for building the multiplier shown in Fig. 2 is 37.5 times and the optimized output after reduction of the circuit should be reached at an output frequency of 30.7 GHz. This means that the total error in scaling is 1.3 percent. The error is very small because the photolithographic technique is one of the most accurate methods to reduce the physical dimensions of a microstrip circuit and also because the dielectric constant of the substrate does not change with frequency.[12]

Figure 5 shows the frequency spectrum of the multiplier from 29.3 to 31.3 GHz. The output is stable and free of spurious signals to the maximum sensitivity of the spectrum analyzer which is 40 dB below the output of the multiplier. Good stability and spurious-free operation are also obtained for the oversize multiplier with an 80-percent efficiency and a power output of 2.5 W at 818 MHz.

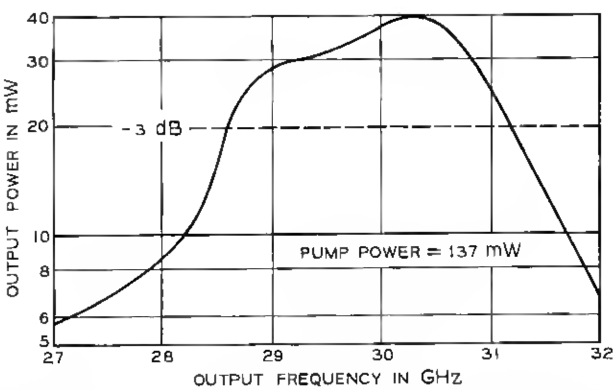

Fig. 4—Tuned output power versus frequency of multiplier for fixed pump power of 137 mW.

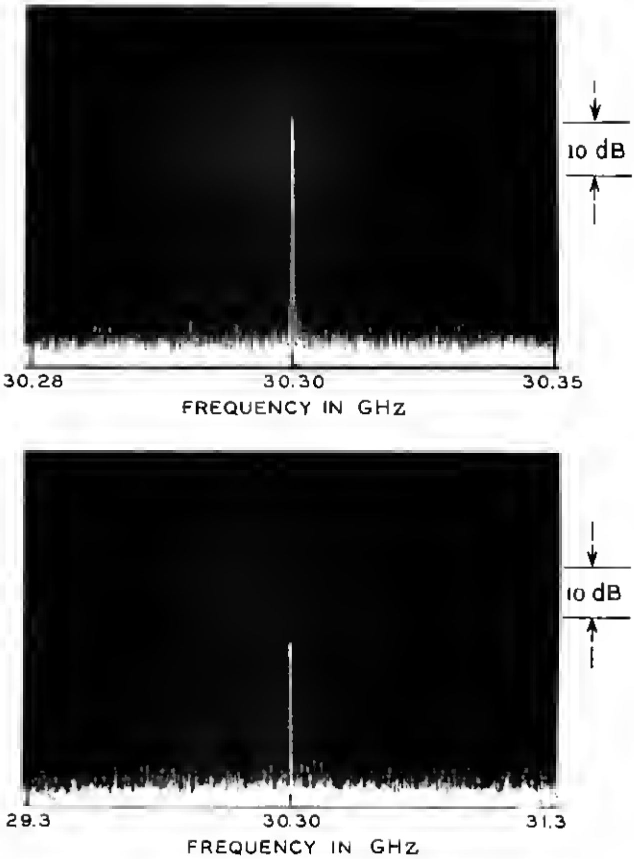

Fig. 5—Output spectrum of multiplier from 29.3 to 31.3 GHz.

IV. CONCLUSIONS

Hybrid integrated multipliers on a dielectric substrate can now be built with output frequencies up to 30 GHz. The power levels and the overall efficiencies which are obtained with a single planar diffused gallium arsenide diode are useful for many future millimeter-wave systems applications.[2,13] Scaling of oversize circuits is a powerful technique for building optimized integrated millimeter-wave circuits.

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